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Design Considerations and Research Needs for Expanding the Current Perceptual Model of Spatial Orientation into an In-Cockpit Spatial Disorientation Warning System

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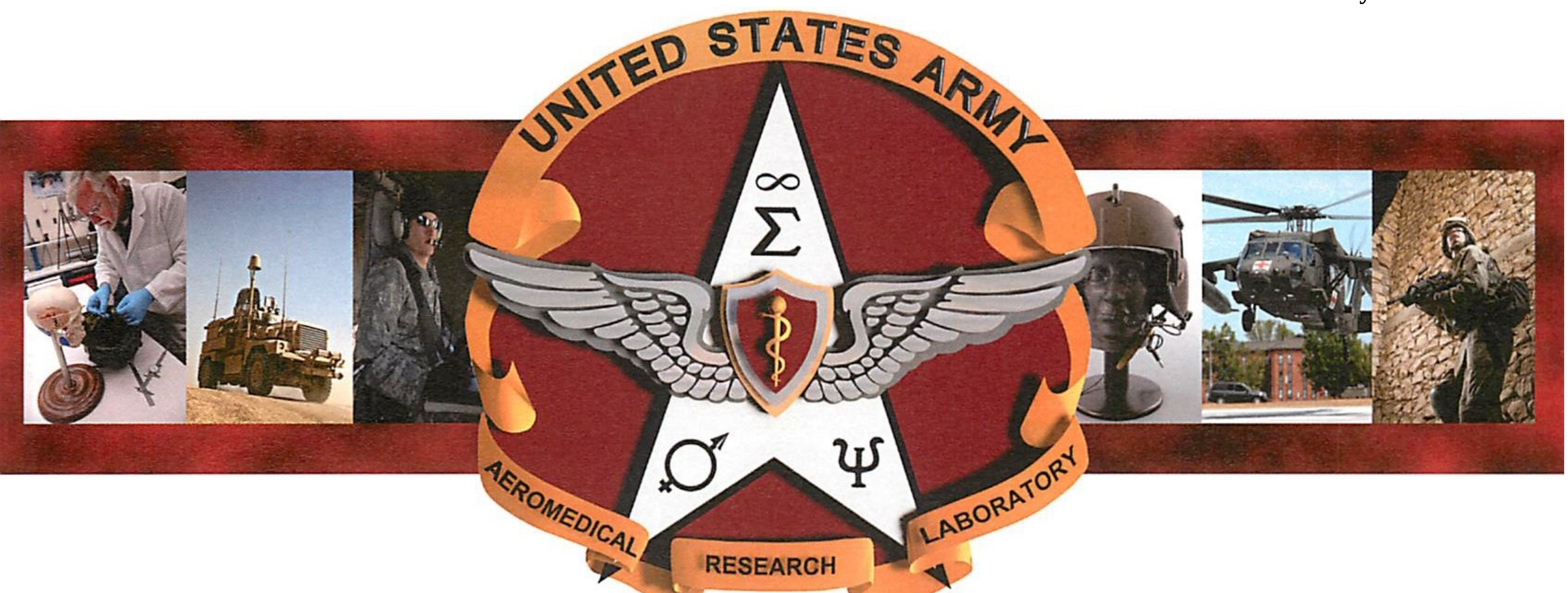

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14. ABSTRACT

Spatial disorientation (SD) in flight occurs when a pilot incorrectly perceives the orientation or motion of the aircraft, due to vestibular, somatosensory, or visual illusions. Mathematical models of SD predict a pilot's perceived orientation, based on quantitative analysis of external and internal factors, e.g., a resultant gravitoinertial force exerted on a pilot's body versus the vestibular response to the force. The current application of mathematical modeling involves analyzing flight mishaps post-hoc to determine whether the pilot likely experienced SD in the moments prior to the mishap. Lawson, McGrath, Newman, and Rupert (2015) propose applying current modeling principles to the creation of an in-cockpit warning system to allow for proactive prediction and pilot warning of imminent SD and prevention of SD-related mishaps. The present report discusses the feasibility, desirability, and design considerations of the proposed expansion of the current model into an in-cockpit SD warning system.

15. SUBJECT TERMS

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Spatial Disorientation and Perceptual Modeling

Spatial disorientation (SD) is a frequent and serious problem in military aviation, costing at least 40 lives per year, and causing significant financial burden (McGrath, Rupert, & Guedry, 2002). Spatial disorientation occurs when a pilot has an incorrect perception of the orientation or motion of the aircraft relative to the Earth (Benson & Stott, 2006). Through decades of research, scientists have developed an understanding of the sensory systems involved in spatial perception and how these systems can be fooled by dangerous perceptual illusions when piloting aircraft.

Spatial disorientation researchers have developed an approach to the problem of SD: a mathematical model that compares veridical information about flight conditions (such as acceleration information provided by flight instruments) with mathematical predictions of perceived orientation (e.g., Newman, Lawson, Rupert, & McGrath, 2012). The information provided by the model is used to analyze flight mishaps post-hoc and determine whether SD was the primary contributor (Newman et al., 2012). The perceptual model can serve as a heuristic SD countermeasure by aiding in visualization of SD mishaps, which improves SD awareness and offers the opportunity for prevention. This paper considers another practical application of the model.

Proposed Innovations to the Current Perceptual Model

In a recent paper, Lawson, McGrath, Newman, and Rupert (2015) propose expanding the current model into a proactive in-cockpit warning system, which would provide warnings of imminent SD, predicted by system calculations. This innovation would transform unrecognized SD into recognized SD, which could prevent entry into a dangerous condition where situational awareness is lost.

The ideal SD warning system would continuously analyze veridical flight conditions and estimated pilot perceptions to determine if SD is likely to occur. Spatial disorientation is often caused by one or more perceptual illusions (e.g., somatogravic illusions; Benson & Stott, 2006), which typically involve the vestibular, somatosensory, and visual systems. Each illusion is characterized by a certain type of changing flight condition and a misperception of the change (e.g., an aircraft enters into a banked turn, but the pilot perceives that the aircraft is flying straight and level; Benson & Stott, 2006). If a pilot's actions and the current flight conditions were predictive of a particular illusion, an in-cockpit SD warning system would identify the circumstances as such and provide the pilot with a warning (e.g., informing the pilot that if he or she feels pitched up, the instruments should be checked immediately).

The recent paper by Lawson et al. (2015) describes four general requirements for developing the proposed system. For example, one of the criteria described by Lawson et al. is the requirement for the model to receive inputs about the state of the user, e.g., whether the pilot is looking at the primary flight displays. The general requirements discussed in Lawson et al. (2015) are aspects of the model that would need to be met for the proposed new application of the model to work. In addition to establishing the basic and necessary features of the model-based warning system, it is important to determine how it should be designed to optimize human and machine performance.

Expert Consideration of the Proposed System

To address the challenges of designing a new type of model-based display for potential implementation in aircraft, a small group of experts met in the summer of 2015 at the invitation of Drs. Angus Rupert and Ben Lawson[1]. The meeting consisted of spatial orientation experts, modeling experts, and other supporting personnel, who met at the U.S. Army Aeromedical Research Laboratory (Table 1). An audio recording of the event was used as a guide for writing this report. This report serves as a summary of the key topics discussed, beginning with the current need for an in-cockpit SD warning system.

Table 1. Table of Attendees

NAME	TITLE	AFFILIATION
Angus Rupert	Medical Research Scientist	U.S. Army Aeromedical Research Laboratory (USAARL), Fort Rucker, AL
Ben Lawson	Research Psychologist	USAARL
Brad McGrath	Aerospace Engineer	University of Canberra, Australia; Embry-Riddle Aeronautical University, Daytona Beach, FL
Mike Newman	Research Scientist	Environmental Tectonics Corporation (ETC), Philadelphia, PA
Torin Clark	Assistant Professor	Aerospace Engineering Sciences, University of Colorado
Kara Beaton	Aerospace Engineer	NASA Johnson Space Center, Neurosciences Lab Houston, TX
Gary Zets (Supporting)	President and founder of Engineering Acoustics Incorporated (EAI)	EAI, Casselberry, FL
Casey Harris (Supporting)	Engineering Technician	USAARL/Oak Ridge Institute of Science and Education (ORISE), Oak Ridge, TN
Deahndra Grigley (Supporting)	Research Assistant	USAARL/ORISE, Oak Ridge, TN
Linda-Brooke Thompson (Supporting)	Research Assistant	USAARL/Laulima Government Solutions, LLC, Orlando, FL

[1] This group is called the Spatial Orientation Modeling Expert Workgroup (SOMEW). This meeting was supported by Program Executive Office Aviation (Huntsville, AL), under its Small Business Innovation Research program. The group met on several important SD problems and countermeasures, one of which is reported here. The first meeting was small due to government meeting/travel restrictions, but a larger meeting of approximately 50 SOMEW participants is planned for January 2017 in Pensacola, FL.

Current Need for an In-Cockpit SD Warning System

Pilots and aircraft are commonly equipped with devices that assist them in avoiding mishaps (e.g., visual displays that provide information about orientation). However, unplanned in-flight events can cause the pilot to fail to receive veridical information about flight conditions and state of the aircraft. This situation can cause SD and would warrant an SD warning system. A common problem in-flight that can lead to SD is pilot distraction. Pilots often have high workloads in-flight and may not look at the instruments frequently enough or cognitively attend when looking (Lawson et al., 2015).

In situations where the pilot has insufficient awareness of the state of the aircraft and current flight conditions, an in-cockpit SD warning system would have obvious benefit. Such a system should be designed to optimize human-machine performance. The following sections will discuss ideas for the optimal design of an in-cockpit SD warning system.

Model Design

Should the Display be Multisensory?

Unisensory displays are commonly used to cue important information to pilots; however, multisensory cueing is more natural and intuitive. We continuously use multiple sensory systems to maintain spatial orientation and motor coordination in our daily lives. We also use multiple sensory systems to warn us of danger, which has obvious relevance to an SD warning system.

Each sensory system is best suited for certain kinds of dangerous situations (Lawson, 2014). For example, the auditory sense is best suited for alerting attention to danger outside of the visual field, e.g., a tiger creeping up from behind. The visual system is best suited for warning us of distant danger, e.g., a tiger spotted 50 yards away. Using cues from multiple sensory systems to maintain spatial orientation and situation awareness is a natural process. This natural tendency would likely translate to intuitive understanding and use of a multisensory SD warning system.

Multisensory displays may provide more safety assurance than unisensory displays, as information provided by a single sensory system may not always be adequately or correctly perceived by the user. For example, Brill, Rupert, and Lawson (2015) found that study participants had difficulty accurately perceiving auditory cues during ambient noise. Participants showed significantly better perception of audiotactile cues under the same conditions. The use of multisensory cues in this study improved target localization. In a real-world situation, improving perceptual accuracy through multisensory cueing may prevent SD mishaps.

Research has shown that redundancy of information (i.e., cueing pilots with multiple sensory systems) tends to improve performance (Oskarsson, Eriksson, & Carlander, 2012). A multisensory cueing display in an in-cockpit SD warning system would likely benefit the intuitiveness and efficacy of the system.

Employment of each sensory system in cueing information to pilots

Determining the optimal design of an in-cockpit SD warning system has the potential to be a complex process, especially if multisensory cueing is employed. In addition to determining which sensory systems to exploit, the method of cueing must be determined (i.e., how each cue will be presented). The following sections will explore possibilities for the employment of auditory, visual, and somatosensory (tactile and kinesthetic) cues for use in an in-cockpit SD warning system.

Auditory cueing

The auditory sense is commonly used in flight for communication purposes. An auditory warning cue must be designed to avoid confusion with necessary radio communications and may be verbal or non-verbal information. In flight, pilots are presented with a large number of non-verbal auditory signals and must remember what each signal means. Presenting yet another non-verbal cue may further complicate a pilot’s memory load (Doll & Folds, 1986).

Contrary to non-verbal cues, verbal cues can provide pilot with specific information about current SD problems, eliminating the need to memorize the meaning of the cue. If presenting a verbal warning to pilot, consideration must be given to whether the warning should simply inform the pilot of the problem or advise him or her on the appropriate corrective control.

Consider the following hypothetical example of an SD situation and how a cockpit SD warning system may present an auditory cue. A helicopter pilot has designated to a specific hover position and plans to hover without drifting. The warning system detects that the lateral drift information provided by the aircraft instruments is inconsistent with the pilot’s perception of the motion of the aircraft (pilot perception estimated by model calculations). Due to the designated hover point, the system calculates that the pilot is unknowingly drifting to the left during the hover task. In a situation such as this, there are several auditory options for alerting the pilot to his or her disorientation. The verbal cue may simply indicate to the pilot that he or she is disoriented *or* may *also* give the pilot instructions to move the aircraft to the right.

The information given by the cue should be brief and simple. If the warning cue were to provide a detailed description of the illusion and correctional instructions, the pilot may become distracted and overwhelmed. Auditory distraction is a common problem for pilots in the cockpit; giving *detailed* verbal instructions to a pilot already engaged in verbal communication may not prove to be helpful.

In addition, the efficacy of auditory cueing may be strengthened if the auditory cue were presented spatially concordant with the target or threat of interest (e.g., the message “threat at 3 o’clock” presented spatially at 3 o’clock). For example, an abstract cue would require different cognitive processing than a spatial cue on the body presented in the 3 o‘clock orientation.

Visual cueing

The human visual system is commonly employed for cueing important information in flight. A pilot must pay close attention to the visual displays providing him or her with important information about the orientation of the aircraft, flight conditions, etc. If a spatial disorientation warning system were incorporated into the cockpit, how would the visual aspect of this system be differentiated from the multitude of visual cues already being provided by the flight displays? A natural option is to present visual warning cues concordant with the presentation of auditory warning cues. For instance, in the spatial disorientation scenario described above, if the pilot is told to “check drift”, the system could be programmed to illuminate the relevant instruments simultaneous to the presentation of the auditory cue. This type of bimodal cueing (audiovisual) has been shown to be more effective at attracting and sustaining user attention compared to unimodal (visual or auditory only) cueing, even in a high workload condition (Santangelo & Spence, 2007). Another important design consideration is the appearance of the visual cue (e.g., color and size). Human factors experts should be consulted to ensure that the appearance optimizes detection and perception.

Somatosensory cueing

Tactile

Somatosensory cueing is a less common in-flight practice, relative to the other cueing modalities discussed. The somatosensory system processes sensations from the skin, muscles, and joints. Tactile cueing, a subset of somatosensory cueing, is effective for providing warning and safety information to pilots (Lawson et al. 2015; Rupert, 2000). Responding to tactile cues from a cockpit warning system should be intuitive to users as we subconsciously use tactile information in our daily lives to maintain orientation continuously while sitting, standing, and moving through the world. To effectively present tactile information in a cockpit SD warning system, a few key principles from tactile research should be considered.

Tactile displays typically cue information through the use of small vibrators called tactors. Tactile displays have been demonstrated as effective at signaling information about spatial orientation and directional threats (Brill, Lawson, & Rupert, 2014). In communicating to a pilot to turn his or her attention in a certain direction, the tactile cue is typically presented on the side of the body towards which the aircraft is moving.

For application in a cockpit SD warning system, directional cues may be desired if the intent is to help the pilot steer away from a collision when the system detects that the pilot is disoriented. If the pilot is to be provided with such instructions, ideally the vibration of the tactile cue should occur on the side of the pilot’s body opposite to the direction the aircraft needs to be turned to achieve correct orientation. For example, in the scenario described earlier in this report (i.e., aircraft is erroneously drifting to the left during a hover task), if the pilot needed to translate the aircraft to the right to eliminate drift, the tactile cue should vibrate on the left side of the pilot’s body (i.e., the direction of the threat). This concept is analogous to lane deviating rumble strips used on roadways.

A concern sometimes raised concerning tactile cueing is that it is subject to habituation, i.e., a decline in the sensitivity to a given stimulus over time. Kelley, Grandizio, Estrada, and Crowley (2014) found that using tactile cues during 12 hours of continuous flight did not cause a decline in detection or response to tactile stimuli. In the study, tactile cues were provided to cue pilots of undesired aircraft motion, e.g., drift. Kelley et al. (2014) state that setting the parameters of the tactile cueing system to activate cues only when aircraft motion exceeds a set limit may avoid extended periods of repetitive stimuli and, subsequently, habituation.

Finally, consideration must be given to whether tactile cues should be presented alone or in combination with the presentation of other sensory cues. Research has shown that presenting users with audiotactile or tactile-visual cues resulted in improved operator performance, compared to presentation of audio, visual, or tactile cues alone (Brill et al., 2015; Ngo, Pierce, & Spence, 2012; Sklar & Sarter, 1999).

Kinesthetic

The kinesthetic (joint, muscle, and tendon) sensory system is a subset of the somatosensory system. Kinesthetic sensations relate to a person's natural awareness of limb positions, movements, and muscle tensions. Kinesthetic cueing is not common in aircraft, relative to the other sensory modalities discussed, but has been demonstrated as an effective cue during vehicle control (Ruff, Draper, Lu, Poole, & Repperger, 2000). Ruff et al. found that kinesthetic cues provided through a "force feedback joystick" significantly improved five pilots' reported awareness of mild and severe turbulence during simulated landing of an unmanned aerial vehicle, compared to a condition with no kinesthetic cues provided. The results of this study suggest that kinesthetic cueing is an effective and intuitive method for alerting users to vehicle control challenges. An in-cockpit SD warning system would likely be improved by a kinesthetic cueing component. Further research is needed to determine how kinesthetic cues should be provided in-flight.

Should the Model Include an Automated Recovery Feature?

The employment of multiple sensory systems and redundant cues is effective in increasing awareness and safety (Brill et al., 2015; Ngo et al., 2012; Oskarsson et al., 2012; Sklar & Sarter, 1999). If multiple redundant cues were incorporated into the design of an in-cockpit SD warning system, would disorientation safety concerns be resolved? The answer to this question varies depending on the circumstances. This section will describe the potential safety concerns and solutions and the varying viewpoints surrounding these issues.

The efficacy of any technology involving communication between the user and the system depends on the attentiveness of the user. The attention of the user is often divided due to the high workload associated with piloting the aircraft. Pilot inattention can harm the efficacy of a potential in-cockpit SD warning system, and ultimately cause a mishap. To combat inattention and other factors that may prevent timely action (e.g., inability to decide what action to take), the ideal SD warning system may need to assume partial or full control of the aircraft.

Automated recovery systems are becoming increasingly available for use in military aircraft. The Automatic Ground Collision Avoidance System (Auto-GCAS) is a recently fielded system designed to assume command of the equipped aircraft whenever ground impact is imminent. The system's efficacy for saving lives and aircraft has been demonstrated (Norris, 2015).

The success of the Auto-GCAS serves as an example of the potential benefits of integrating an automated recovery feature into a future in-cockpit SD warning system. Though the proposed SD warning system would ideally circumvent mishaps prior to the need of automated recovery, there are potential situations that would warrant an automated recovery. Situations involving loss of communication between the warning system and the user occur for many different reasons and could require automated safety intervention. Loss of veridical information resulting from damage to aircraft, instrument failure, pilot loss of consciousness, and cognitive overload are examples of such situations. There is also concern that pilots may not trust SD warnings. The SD illusions that are common in flight result in pilots believing they are moving or oriented in a way that is contrary to their actual movement or orientation. The pilot's false perception may be so convincing that he or she believes disorientation warnings to be incorrect. This lack of trust may render the need for an automated recovery feature.

Potential concerns with automation

While automation could help a pilot not trusting his or her instruments, the pilot also needs to trust the automation. Lack of trust in the automation may cause pilots to feel uncomfortable relinquishing control of the aircraft, and in a worst-case scenario, not want to use the system (Lyons et al., 2016).

A recent study of pilot trust in the Auto-GCAS is relevant to the potential challenges of designing an SD cockpit warning system. Lyons et al. (2016) surveyed 15 experimental test pilots who had experienced the Auto-GCAS, asking questions pertaining to the pilots' trust or distrust in the system, and what factors influenced their reasoning. The pilots' answers revealed that trust was most dependent on the Auto-GCAS's ability to avoid false alarms, reliability of the system in effectively avoiding mishaps, and transparency of the system's actions. (Lyons et al., 2016). Results of other studies have also shown that these factors influence trust of automated systems (Dzindolet, Peterson, Pomranky, Pierce, & Beck, 2003; Moray, Inagaki, & Itoh 2000; Schaefer et al., 2014).

Dixon, Wickens, and McCarley (2006) found that willingness to comply with an automated system (i.e., willingness to heed the warnings provided by the system used in their study) decreased significantly as system false alarms increased. This is an important consideration in the design of an SD cockpit warning system, as pilot compliance challenges may result in a rejection of the system. The potential safety benefits of an automated recovery feature are undeniable. However, if the feature is unreliable, prone to mistakes, unpredictable, etc., the usability and desirability of the future in-cockpit SD warning system may be reduced.

Optimal extent of automation

If a fully automated recovery feature were not desired, a partially automated system may be considered. A partially automated system may be more readily accepted by users if the user prefers the ability to disengage the automation in unfavorable situations (e.g., a pilot believes the system has produced a false alarm). Of course, this type of automation would depend on the pilot to make correct judgments about the system's accuracy. As previously explained, pilot judgment is often compromised by SD illusions. Determining the optimal solution will require careful study of false positive and negative model predictions.

Pilots' attitudes towards full or partial automation are an important consideration. Olson and Sarter (2000) surveyed 206 airline pilots with experience flying aircraft with some degree of automation. The survey described a possible future flight system and varying degrees of automation (e.g., "management-by-exception," which allows the automated system to initiate an action without pilot input, but also allows pilot to override the action). The pilots were asked to rate which degree of automation they would prefer to use in 15 different scenarios (the scenarios each represented different factors true to real flight, e.g., high workload). Results showed that pilots preferred to be have the ability to override the automated actions as opposed to full automation with no override capability in all scenarios.

Another important consideration is whether automated features cause pilots to place *too much trust* in the system, which can cause problems such as less attentiveness in flight or tendency to take more risks in flight. Lyons et al. (2016) stated that pilots' trust in the Auto-GCAS may cause more aggressive and brazen flight behavior. This concern may also be applicable to the SD warning system, in general. Could reliance on the warning system to monitor and report danger cause pilots to relax their attentiveness?

Conclusions and Recommendations

This report is not intended to provide absolute solutions to the challenges of creating a new technology, but to serve as a guide to the important design considerations for a future in-cockpit SD warning system. The solutions to the challenges proposed in this report require extensive research and comparison of perspectives, including that of military and aviation researchers, pilots, human factors experts, etc. For example, the developers of Auto-GCAS recognized the importance of ensuring that pilots were comfortable with the automated system and would not view it as a nuisance (Lyons et al., 2016). During the development process, pilots were recruited to participate in flight tests to help determine the optimal time-before-impact with the ground that the automated recovery system should trigger. Determining pilot perspectives in the design of an SD warning system should help to avoid mistrust, which is of significant importance to the efficacy and acceptance of any system involving human-machine interaction.

The topics discussed in this report are based on the views of the SOMEW. After consideration of the evidence, the experts made the following recommendations:

- A reliable orientation-model-based in-cockpit SD warning system would be beneficial to aviators
- The associated warning display should be multisensory

- The unimodal sensory cues that make up the multisensory display should provide concordant information (e.g., 3D spatial cueing instead of a mix of spatial and abstract/symbolic cueing)
- An automated recovery feature could be beneficial if designed carefully

We recommend continued exploration of the potential usefulness of the current perceptual model as part of an in-cockpit SD warning system. If innovation is continued, this report and Lawson et al. (2015) may be consulted as a summary of initial design considerations and a brief archive of relevant research studies. Though this report does not provide absolute solutions to the stated design challenges, it will hopefully be useful to those interested in continued improvement of SD countermeasures in flight.

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